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SEISMIC VELOCITY STRUCTURE AND EVENT RELOCATION IN KAZAKHSTAN FROM OBSERVATION AND MODELING OF SECONDARY P PHASES

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13. ABSTRACT *(Maximum 200 words)*

Data from presumed explosions in Kazakhstan recorded by NRDC/SAS stations were analyzed to model the crustal structure of the region and to examine the use of arrival times of secondary P phases in event location. Data from 20 events were modeled using a reflectivity algorithm. A good fit to the first five seconds of the P wave was obtained in the epicentral distance range of 100 to 300 km. The best fitting crustal model has a velocity in the upper crust increasing from 4.5 km/sec near the surface to over 6 km/sec at 10 km depth and a mid-crustal velocity of 6.5 km/sec at 15 km depth increasing to 6.95 km/sec at 40 km depth. The model is similar to previous estimates of P velocity structure in the region, though with a gentler gradient in the upper crust and a steeper gradient in the lower crust. We used the derived crustal model and the primary and secondary P wave arrival times to relocate events in the region. Utilizing the phase PmP substantially decreases the focal depth uncertainty for many events. Virtually all of the events analyzed are concluded to be surface explosions.

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Introduction

Seismic event location at regional distances has traditionally relied on P wave first arrivals at a large number of stations. However, in the case of a sparse regional network or regional arrays, event location often must be done by incorporating either seismic wave azimuths and/or combined timing of first and secondary arrivals. Previous work on near-regional data from Kazakhstan (Thurber et al., 1989; Li and Thurber, 1991) indicates that secondary P phases can be observed in many seismograms. We have undertaken a study to determine whether or not secondary phases can be accurately identified and modeled, using a combination of polarization analysis and seismogram synthesis, and then utilized to improve event locations.

We seek to study the regional phases Pg, Pn, and PmP from a set of events recorded by the Natural Resources Defense Council/Soviet Academy of Sciences (NRDC/SAS) network in the Kazakhstan region that operated in the years 1987 to 1988 (Figure 1). The network stations, consisting of sets of three-component seismometers, produced about two dozen high quality multi-station recordings of explosions in the epicentral distance range 25 to 450 km (Thurber et al., 1989). Our analysis focuses on data from stations Bayanaul (BAY) and Karkaralinsk (KKL), as station Karasu (KSU) suffered from a serious site effect (Berger et al., 1988) and also was in a region of different velocity structure (Leith, 1987) for which the approximation of a uniform crustal model might not be applicable. A number of secondary P phases have been observed on these seismograms that we believe can be identified as either PmP or Pg.

Previous Research on Crustal Structure in Kazakhstan

A number of authors have examined regional explosion data sets for crust and upper mantle structure in Kazakhstan. An excellent summary of these studies is provided by Ryaboy (1989). This work has shown that the crust in this region has a structure with moderate lateral variations and a crust-mantle boundary depth ranging between 45 and 55 km. Leith (1987) reported a crustal

structure obtained from a Deep Seismic Sounding (DSS) profile near the stations KKL and BAY with a 50 km thick crust and 6 crustal layers, with P velocities increasing monotonically with depth. Priestly et al. (1988) used an inversion of teleseismic P to S converted waves at stations BAY and KKL to obtain a 7-layer P velocity model (assuming a constant Vp/Vs value) generally similar to that reported by Leith (1987), except that station BAY has a slightly higher lower crustal velocity and a slightly lower crustal thickness. Overall, there is evidence for significant crustal and upper mantle heterogeneity in this region, though relatively modest heterogeneity in the immediate vicinity of the Kazakhstan Test Site. Therefore, we believe that any one dimensional crustal model will constitute only a first-order approximation to the actual structure in this region. It is our goal in this paper to examine the range of applicability of a simple one dimensional model for this region by investigating the ability of near-regional reflectivity synthetics to match observed seismic travel times and wave forms. Our focus is on first and secondary P wave arrivals and their potential for regional event location.

Examination of Near Regional Data

The data analyzed in this study were recorded on a set of surface mounted Teledyne Geotech GS-13 short period seismometers, a set of Kinemetrics SV-1 and SH-1 surface mounted intermediate period seismometers, and a set of Geotech 54100 borehole mounted seismometers installed at depths of 66, 101, and 99 m at BAY, KKL, and KSU, respectively (Berger, et. al. 1988). The response of these instruments (Berger et. al., 1988) is virtually flat at the frequencies of interest. The noise spectrum for the three stations is also summarized by Berger et al. (1988). The stations BAY and KKL have similar, and reasonably flat, noise characteristics; the station KSU is considerably noisier at both the high and low ends of the spectrum, which shows up as a ringing effect in the data. The noisiness of the KSU site rendered the data almost unusable; consequently we have not utilized the data from KSU in this paper.

The events used in our analysis are those located by Thurber et al. (1989) using body wave

arrival times and P wave arrival azimuths. Absolute locations are only known exactly for the chemical explosions (Given et al., 1990), but other events are clearly associated with mines or quarries observed in satellite images (Thurber et al., 1989); others can be associated with mines indicated on regional maps. None of the events used are thought to be earthquakes. There is some uncertainty in the epicentral distances of the events analyzed, so we place special emphasis on those events whose locations are most reliable.

A detailed examination of the raw waveforms at the NRDC/SAS stations BAY and KKL indicates the first P arrival is usually followed by one or more distinct secondary arrivals at an interval of about 0.5 to 2.5 seconds in the region between 100 and 300 km from the source. In the region under 100 km distance from the source there are no identifiable secondary P arrivals; only the phase Pg can be identified. At about 120 km distance from the source, however, the secondary arrival PmP appears about 2.5 seconds after the first arrival. The amplitude of this phase relative to the first arrival increases in the region between 120 and 170 km from the source, at which point the second arrival comes about 2 seconds after the first arrival and has twice the amplitude. Between 170 km and the crossover distance of about 245 km the phases Pg and PmP continue converging, and the relative amplitude of PmP keeps decreasing, until at about 260 km distance the two phases are indistiguishable. With increasing distance, the Pg/PmP arrival grows increasingly weak, and beyond 300 km we have difficulty picking secondary phases with any reliability.

To gain confidence in our identification of these arrivals, we carried out a polarization analysis on the secondary phases to determine whether they had the correct polarization expected for P waves from the event azimuth. The polarization analysis was done using the covariance of the horizontal-component seismograms, as described by Thurber et al. (1989). An example is shown in Figure 2. We find that a large fraction of the presumed secondary arrivals have the same azimuth as the first arrival and show significant particle motion rectilinearity. When comparing the data to the synthetics we have considered only the phases that the polarization analysis indicates are from the same azimuth as the first arrival. The polarization analysis and computed arrival times and amplitudes of the synthetic arrivals gives us confidence in our ability to pick the secondary

phases Pg and PmP. Consequently, we have confined most of our attention to making reliable picks on these phases, along with Pn when it is the first arrival.

Crustal Model and Synthetics

After examining the data and making our preliminary picks of the phase arrival times, we next sought to obtain a crustal model which matched the observed phase arrival times and amplitude trends. We computed seismograms using the code of Malik and Frazer (1988). This code was written for computing high frequency (up to 20 Hz) synthetic seismograms over regional distances (0 to 1000 km) a large number of layers. It has been used successfully for a number of different applications, including modeling near source reflection seismograms in the region 0 to 100 km and modeling high frequency regional arrivals at distances of up to 1400 km (Malik and Frazer, 1988). For the various models we are examining, we computed the seismograms in 50 second windows for events under 150 km, 100 second windows for events between 150 and 300 km, and 200 second windows for events beyond 300 km. The synthetic seismograms are windowed, differentiated and low-pass filtered with a Butterworth filter with a 4 Hz corner frequency to suppress high frequency ringing. The NRDC/SAS data had to be converted into a suitable format for comparison with the synthetic seismograms. The seismograms were rotated using azimuth information, then low-pass filtered with a corner frequency of 4 Hz, and then a ten second window around the first P wave arrival was plotted.

In order to constrain our crustal models, we first computed arrival times of Pn, PmP, and Pg to compare to the data. The crustal models were varied systematically to see the effects on the synthetic seismograms. We started with the Leith (1987) crustal model and tested variations in the upper and mid-crustal velocity structure until we obtained good agreement with the Pg first arrivals in the region less than 100 km distance from the events. Pg and PmP arrival times in the distance range 100 to 245 km helped constrain the lower crustal velocities. Near the crossover distance of about 245 km we find considerable waveform complexity in both the data and synthetics. We

focused on the Pn first arrivals in the region between 245 and 300 km in order to ascertain the transition velocity in the regions between 40 and 50 km depth. A transition velocity of 6.95 to 7.05 km/sec was needed in this depth range to model the arrival times of the data. The data require a fairly sharp transition at the crust-mantle boundary region at 50 km depth in order to match the observed difference in the travel times of the different phases. We constrained the upper mantle velocity in the depth range between 50 and 85 km using the Pn arrival times in the region between 250 and 350 km distance. A velocity of 8.25 km/sec in the upper mantle between 55 and 85 km depth gave the best fit to the arrival time of Pn and the observed difference in the arrival times of Pn and PmP in the region beyond 250 km distance. Beyond about 260 km, the principal secondary arrival has the arrival time expected of PmP; however the synthetic PmP considerably exceeds the observed amplitude of PmP in the data.

Our final velocity model is presented in Figure 3. It has an upper crustal layer of about 4.5 km/sec increasing rapidly to over 6 km/sec by 10 km depth, and a lower crust with velocities increasing more gently from 6.50 km/sec at 15 km depth to 6.95 km/sec at 40 km depth. The crust-mantle boundary is at 50 km depth with a transition zone of 8.05 km/sec in the region between 50 and 55 km depth. The upper mantle has a P velocity of about 8.25 km/sec in the region between 55 and 85 km depth. Below this depth, the data do not enable us to constrain the velocity structure, and we have used the structure obtained by Goldstein et al. (1992). We have assumed a constant value for Vp/Vs of 1.73 throughout the model. Overall, our final model looks very similar to that obtained from the deep seismic soundings (dashed lines in Figure 3).

The fit of the data to the synthetics is quite good in the region between 100 and 280 km (Figure 4). This model matches the Pg, PmP, and Pn arrival times within about 0.3 second for most of the phases seen on the seismograms. Under 100 km, we get very good agreement with the Pg first arrival times; however, we find that the first arrivals on the synthetics are larger in amplitude than the data compared to the initial coda. We can attribute this to wave scattering and conversion not modeled by the reflectivity synthetics. Between 100 and 200 km, the first arrival times and the overall waveform envelopes show good agreement; however, the arrival time

difference between Pg and PmP is somewhat greater in the synthetics than in the data for the region under 150 km, and somewhat less in the synthetics than in the data for the region beyond 150 km. The model shows the best agreement in the region between 180 and 245 km, where the synthetics match both the arrival times and amplitudes of Pg and PmP. At the crossover distance of 245 km, we find that the Pg, Pn, and PmP phases all arrive in the first second of the record on both the synthetic and the data records. Between 250 and 280 km, the synthetic matches the arrival time of Pn and PmP well; however, the Pn amplitude of the synthetics underestimates that of the data, while the synthetic PmP amplitude exceeds that of the data. Beyond 300 km we have difficulty matching the synthetics to the data: every realistic model which matches the Pn and PmP arrival times in the region under 300 km distance gives a PmP amplitude which is much greater than that observed in the data beyond 300 km. We believe that lateral heterogeneity probably renders the assumption of a simple layered model questionable in the distance range beyond 300 km. Therefore, we believe that using a single layered crustal model, as required for the reflectivity synthetics, is probably inappropriate for events in the distance range beyond 300 km.

Event Relocation Using the Phases Pg, Pn and PmP

Previous empirical and theoretical work on regional event location in Kazakhstan (Thurber et al., 1989; Li and Thurber, 1991) has demonstrated the potential of secondary P arrivals for improving constraints on regional event locations. Thurber et al. (1989) made use of some secondary Pg phases in their location work. With an improved crustal model for Kazakhstan (Figure 4) and a careful assessment of Pg and PmP secondary arrivals in the data supported by synthetic seismogram modeling (Figures 3 and 5), it is appropriate to reevaluate the locations of the regional events in Kazakhstan. Event locations were derived in the same manner as described by Thurber et al. (1989), incorporating arrival azimuth information and utilizing the location algorithm TTAZLOC (Bratt and Bache, 1988).

To evaluate the utility of PmP for event location, all the events shown in Figure 1 for which

PmP could be identified were relocated using the new velocity model, both with and without the phase PmP. We note that PmP was identified on nearly half the seismograms. Initially, the events were relocated with focal depth fixed at 0 km, as had been done by Thurber et al. (1989) for all but the three chemical explosions (Given et al., 1990). The event locations showed little change, with differences averaging less than 4 km in latitude and 5 km in longitude. Overall, the RMS residual for all PmP observations was about 0.35 sec. For comparison, the RMS residual for all Pn and Sn observations were 0.25 and 0.50 sec, respectively. Thus the new PmP arrivals times were quite consistent with the previous data. We also note that estimated location uncertainties decreased slightly when PmP observations were added, but this can be attributed to the increased number of degrees of freedom due to adding PmP.

The theoretical study of Li and Thurber (1990) indicates that PmP arrival times can provide significant constraint on source depth for regional events recorded by a sparse network. Therefore we have recomputed the event locations with focal depth unconstrained both with and without the PmP observations. The RMS residuals from the constrained focal depth location results above were adopted as a priori values for the data variances. As in previous studies (Jordan and Sverdrup, 1981; Bratt and Bache, 1988; Thurber et al., 1989), a priori information was given a K-weight of 8.

The location results with focal depth free are indicated in Table 1. The epicenter locations were again quite similar with or without PmP; all events had epicenter differences les than 5 km. Epicenter uncertainties were generally reduced with PmP, but not substantially. The situation for focal depth was quite different, however. Although computed depth differences were not significant, nearly half of the events had their depth uncertainty estimate reduced by a factor of 1.5 or greater when PmP observations were included. Thus the PmP observations do provide useful constraint on source depths at these near-regional distances.

An important issue implicit in this discussion is the confidence that these events are explosions and not earthquakes. In Table 2, independent information on or associations of these explosions with mines or quarries is indicated. Two of the events are the 1988 chemical

explosions, and suspected source areas for seven other events had been identified previously by Thurber et al. (1989) from satellite images (mines at Ekibastuz and Balkash). Of these, events 871351035, 871410916, and 871460833 were also shown to have spectral modulation typical of ripple-fired blasts by Hedlin et al. (1989). In addition, one event (871430849) is thought to have been a blast at a known quarry in the town of Karagayly (Given, personal communication). Of the remaining four events, event 871351035 is located within 4 km of a mapped mine at the town of Yuzhnyy on the 1983 ONC navigational chart for the region, while event 871410916 is located within 10 km of two mapped mines at the town of Molodezhnoye. Of the other two events, 871340936 occurred in the Karaganda area, known for mining, at a time of day typical for mine blasts. Only event 871460531 is "suspicious" due to its time of occurrence, although the location results are not inconsistent with a surface focus.

Conclusions

Using a reflectivity synthetic seismogram code (Malik and Frazer, 1987), we have modeled primary and secondary P phases for a data set from near-regional events recorded in 1987 and 1988 by the stations BAY and KKL of the former NRDC/SAS network. An analysis of wave polarization was used to help identify the secondary phases, primarily PmP. A new layered crustal model for the region was developed to improve the fit to the arrival times and waveforms of these phases. We can match a Pg first arrival and a PmP second arrival on most of the seismograms in the region between 100 km and the crossover distance of 245 km with an arrival time misfit on the order of 0.3 seconds, and the relative amplitudes are also well matched. Beyond the crossover distance, we are able to model Pn and PmP arrival times with comparable fit, but we have difficulty in matching the observed amplitude of the phase PmP beyond 300 km, presumably due to effects of lateral heterogeneity. A secondary Pg phase is only observed in the range just beyond the crossover distance.

Our crustal model for the Kazakhstan region has a 4.5 to 5.5 km/sec upper crust, a middle

and lower crust that increases in velocity from 5.8 to 7.0 km/sec, and a crust-mantle boundary at about 50 km depth. A relatively sharp crust-mantle transition was needed to match the observed difference in the Pn and PmP arrival times. The uppermost mantle has a velocity of 8.05 km/sec between 50 and 55 km depth, increasing to 8.25 km/sec in the region between 55 and 85 km depth. The near-regional data do not constrain the structure at greater depths.

The new velocity structure and PmP observations obtained from this study were used to relocate events in the distance range up to about 300 km from the stations. It was found that adding the phase PmP reduces the uncertainty for event depth in a large number of cases, with relatively little effect on epicenter uncertainty. None of the events can be conclusively demonstrated to be earthquakes, based on their focal depths and associations with active mines and quarries, though one event can not be confidently classified as an explosion.

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Table 1. Comparison of event locations without versus with PmP observations with focal depth free

	Without PmP						With PmP					
Event (yr-day-hr-mn)	Latitude (°N)	Longitude (°E)	Depth (km)	Semi-major axis (km)	Semi-minor axis (km)	Depth axis (km)	Latitude (°N)	Longitude (°E)	Depth (km)	Semi-major axis (km)	Semi-minor axis (km)	Depth axis (km)
871340936	50.199	73.964	0.0	45.2	10.7	2140.2	50.204	73.958	9.3	39.8	4.7	11.0
871350908	51.804	75.593	0.0	31.8	24.7	12.1	51.793	75.615	0.0	32.9	24.6	11.1
871351035	49.320	72.886	6.1	14.1	5.4	11.3	49.299	72.873	5.7	10.8	4.7	6.2
871410916	50.790	73.214	0.0	65.7	5.1	64.8	50.793	73.251	0.0	12.2	5.4	10.2
871430849	49.319	75.689	2.9	11.8	4.5	11.8	49.321	75.699	1.1	9.2	3.9	7.9
871450926	51.642	75.545	0.0	24.5	13.0	10.6	51.640	75.549	0.0	23.1	11.5	8.8
871450956	51.788	75.567	0.0	33.9	15.6	12.7	51.786	75.574	0.0	32.2	14.3	11.3
871460531	51.950	74.937	0.0	30.5	17.1	13.6	51.949	74.917	0.0	28.7	15.8	12.0
871460833	51.671	75.575	0.0	25.3	12.2	16.0	51.663	75.591	0.0	26.9	12.6	12.4
871621241	51.379	75.525	0.0	14.2	9.9	16.7	51.368	75.528	0.0	13.4	8.9	8.3
872390938	46.772	77.354	0.0	83.7	7.9	45.6	46.767	77.351	0.0	59.9	7.3	31.8
872450700	50.281	72.029	0.0	69.7	6.6	43.6	50.295	71.993	2.6	36.4	6.1	21.9
872450927	50.018	77.230	0.0	4.9	3.1	8.4	50.011	77.241	0.0	4.4	2.6	6.6

Table 2. Association of events with known man-made sources

Event	Association
871340936	Uncertain
871350908	Ekibastuz mine
871351035	Yuzhnyy mine
871410916	Molodezhnoye mine
871430849	Karagayly quarry
871450926	Ekibastuz mine
871450956	Ekibastuz mine
871460531	Uncertain
871460833	Ekibastuz mine
871621241	Ekibastuz mine
872390938	Balkash mine
Chemex1	Known explosion
Chemex2	Known explosion

Figure Captions

Fig. 1 Map of the Kazakhstan region showing stations BAY and KKL of the NRDC/SAS network and the locations of events analyzed.

Fig. 2 Polarization analysis for 5 seconds of an example event showing estimated arrival azimuth (thin solid line) and calculated particle motion rectilinearity (broad shaded line) for the Pn, Pg, and PmP phases. Arrival azimuth ranges are plotted for the range $\pm 90°$, while rectilinearity is plotted in the upper portion with the range 0 to 1.

Fig. 3 Final velocity structure model for the Kazakhstan region (solid line) compared to the initial model from Leith (1987) (dashed line).

Fig. 4 Record section of synthetic seismograms at 100, 150, 200, 250, and 300 km distance. A reducing velocity of 7.5 km/sec was used.

Fig. 5 (a to e) Comparison of NRDC/SAS data with reflectivity synthetic seismograms at 105, 156, 197, 257, and 301 km distance. Time axis is in seconds; amplitude scale is arbitrary.

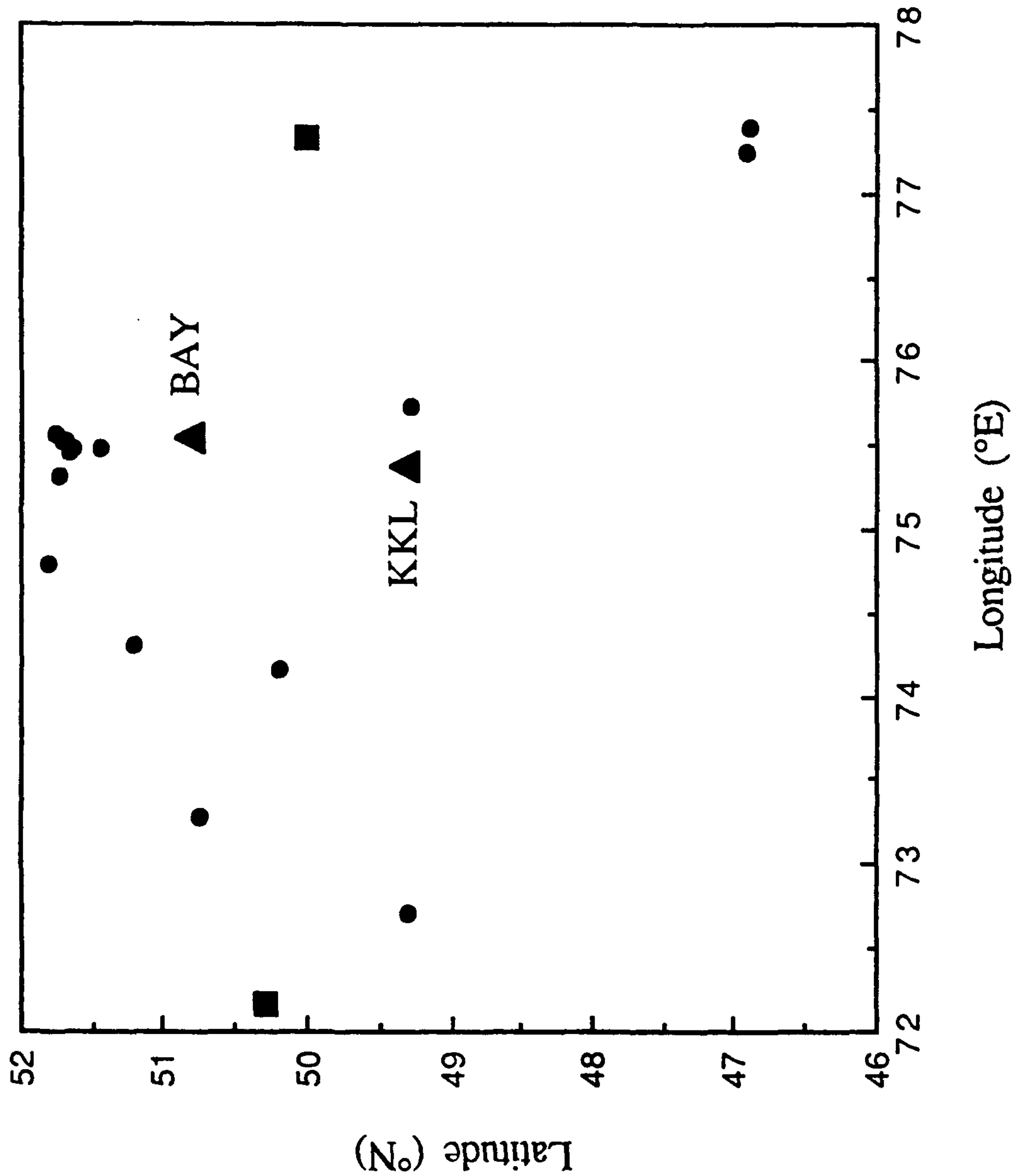
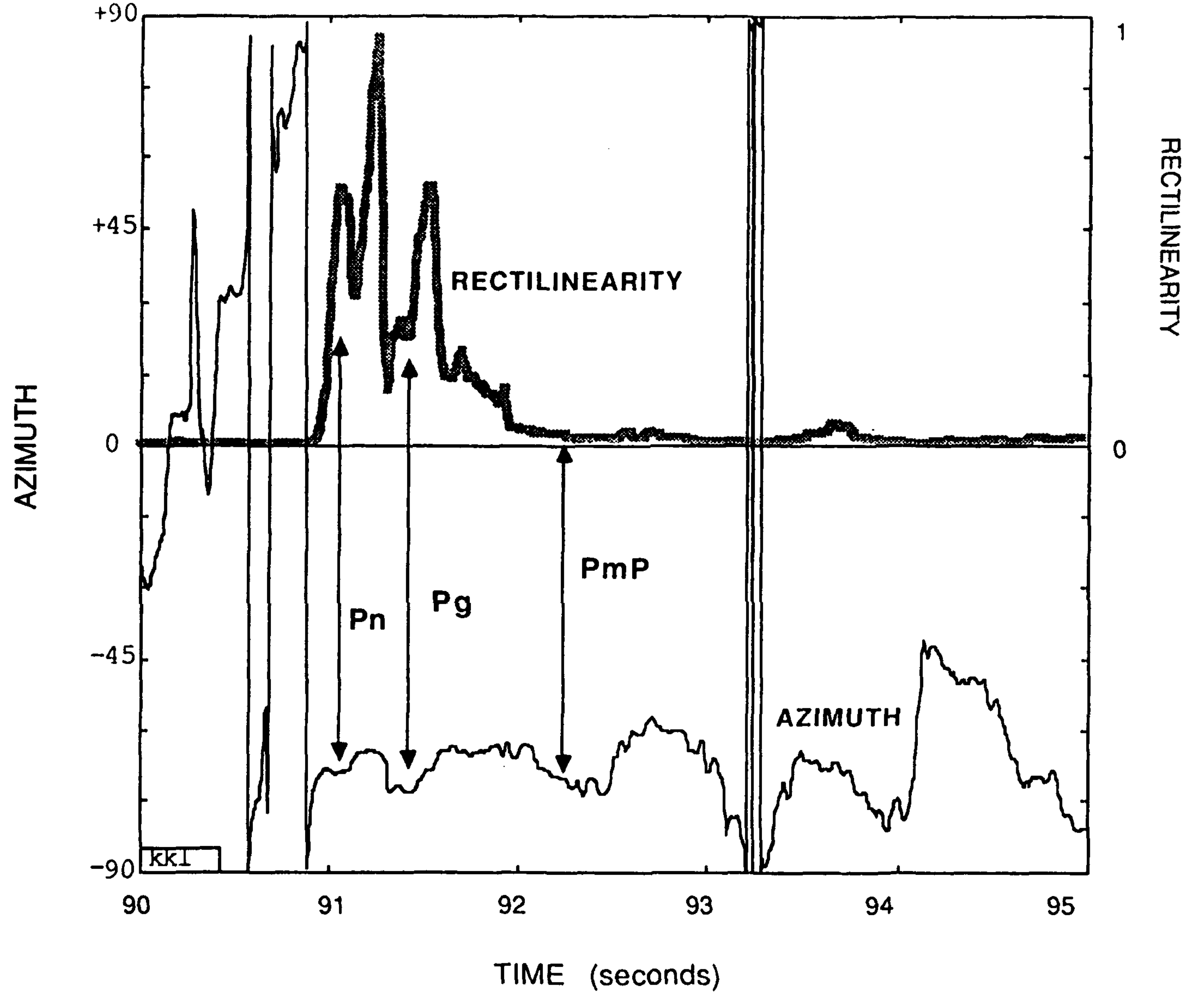

BAY
KKL
52
51
50
49
48
47
46
72
73
74
75
76
77
78
Latitude (°N)
Longitude (°E)

FIGURE 1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+45
0
-45
-90
AZIMUTH
1
0
RECTILINEARITY
RECTILINEARITY
AZIMUTH
Pn
Pg
PmP
kkI
90
91
92
93
94
95
TIME (seconds)

FIGURE 2

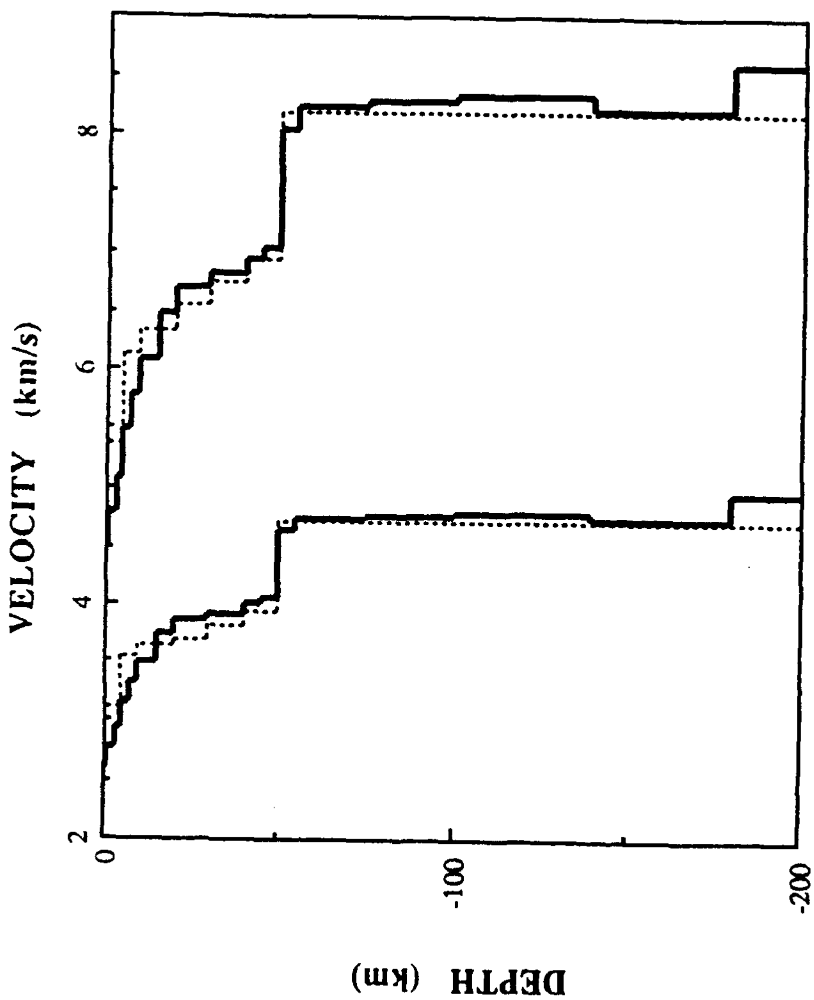
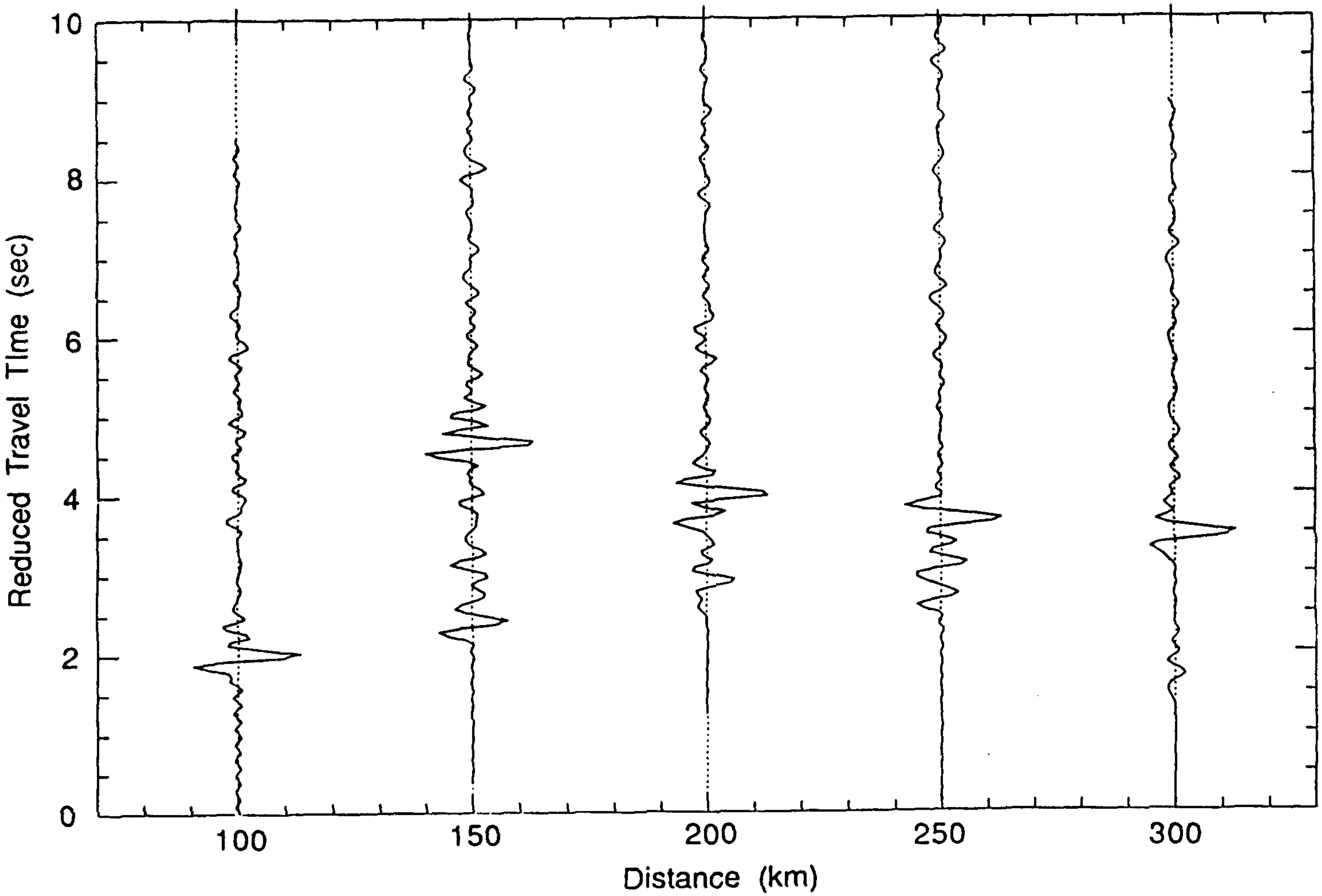


FIGURE 3



10
8
6
4
2
0
Reduced Travel Time (sec)
100
150
200
250
300
Distance (km)

FIGURE 4

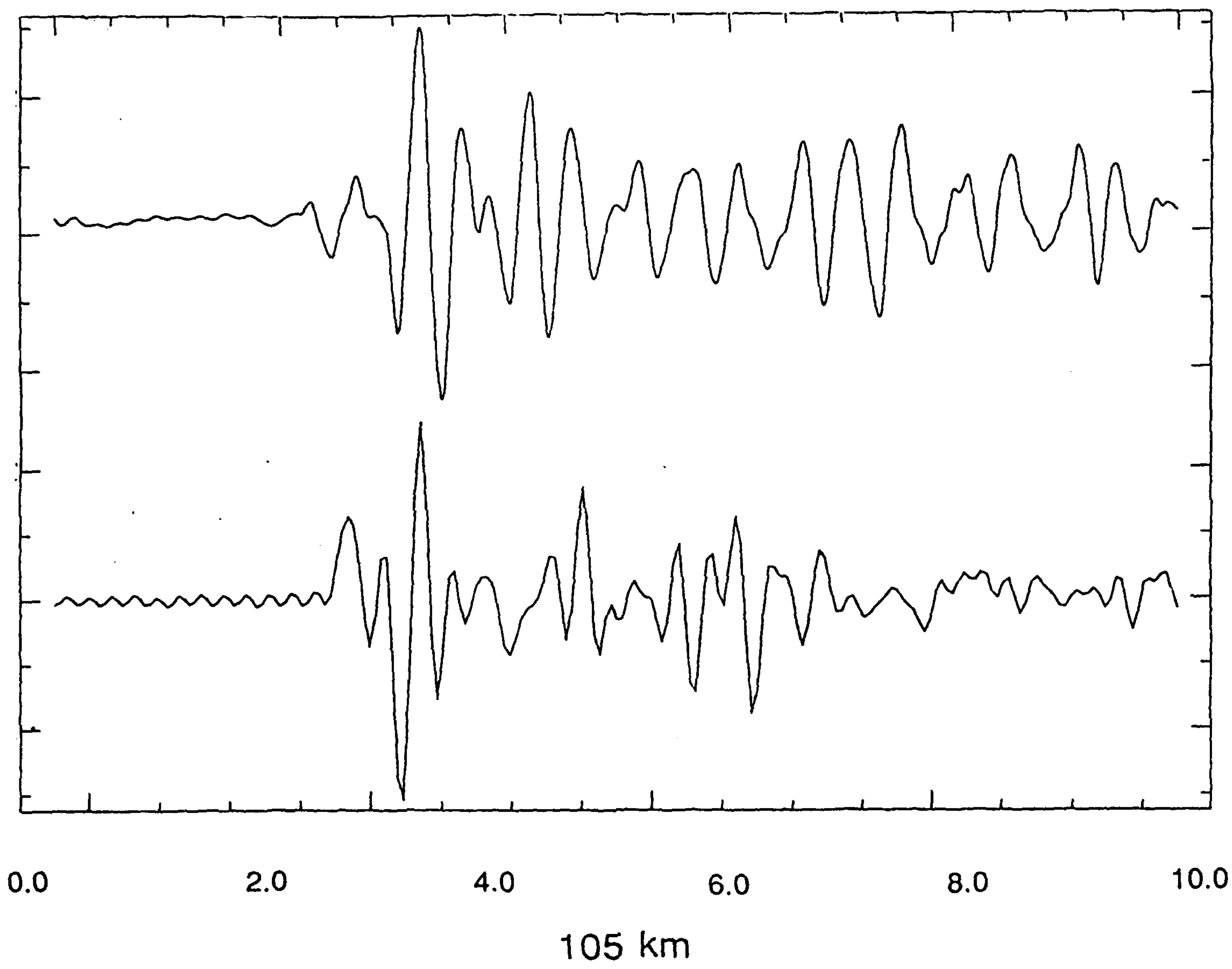
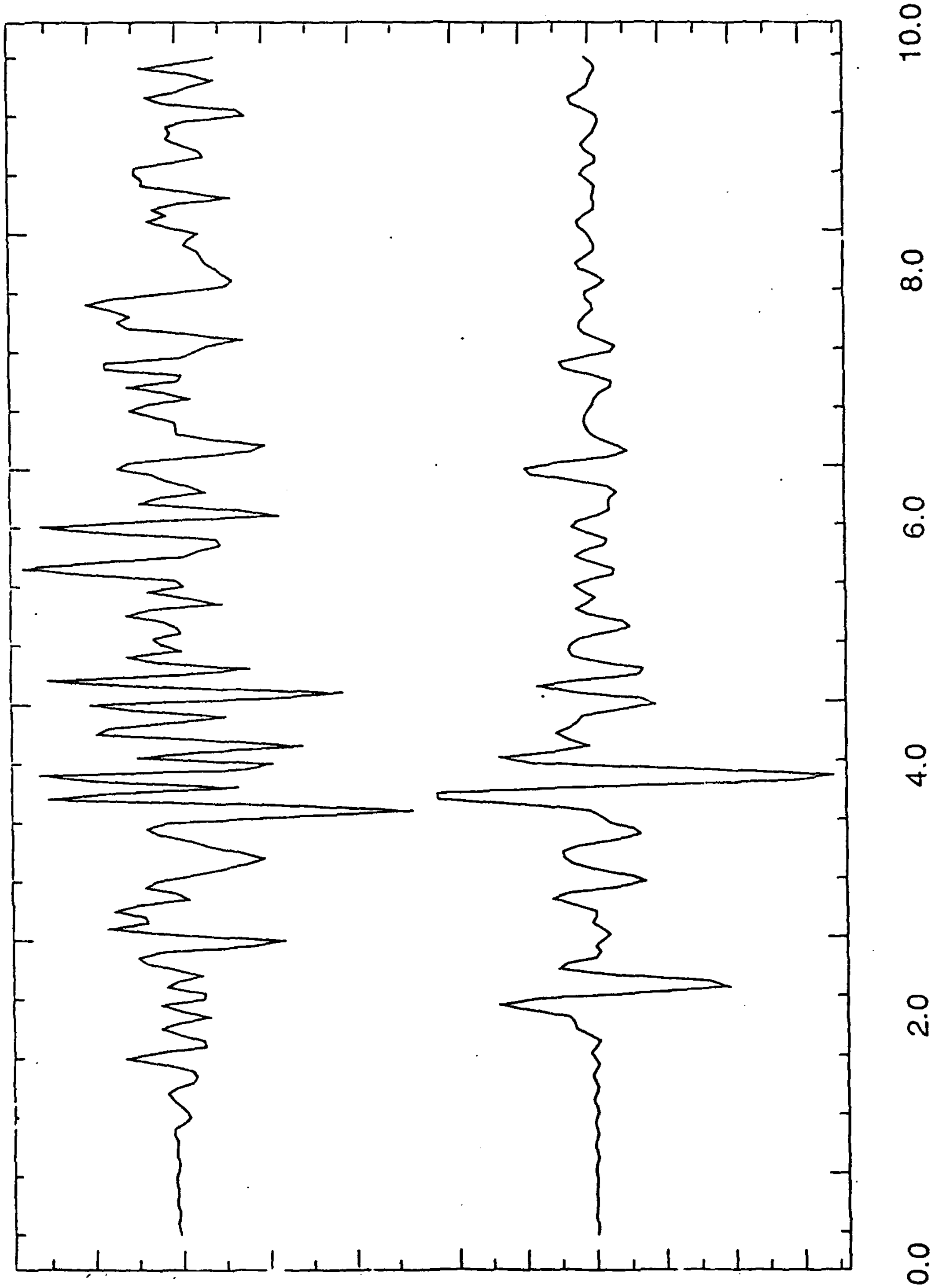
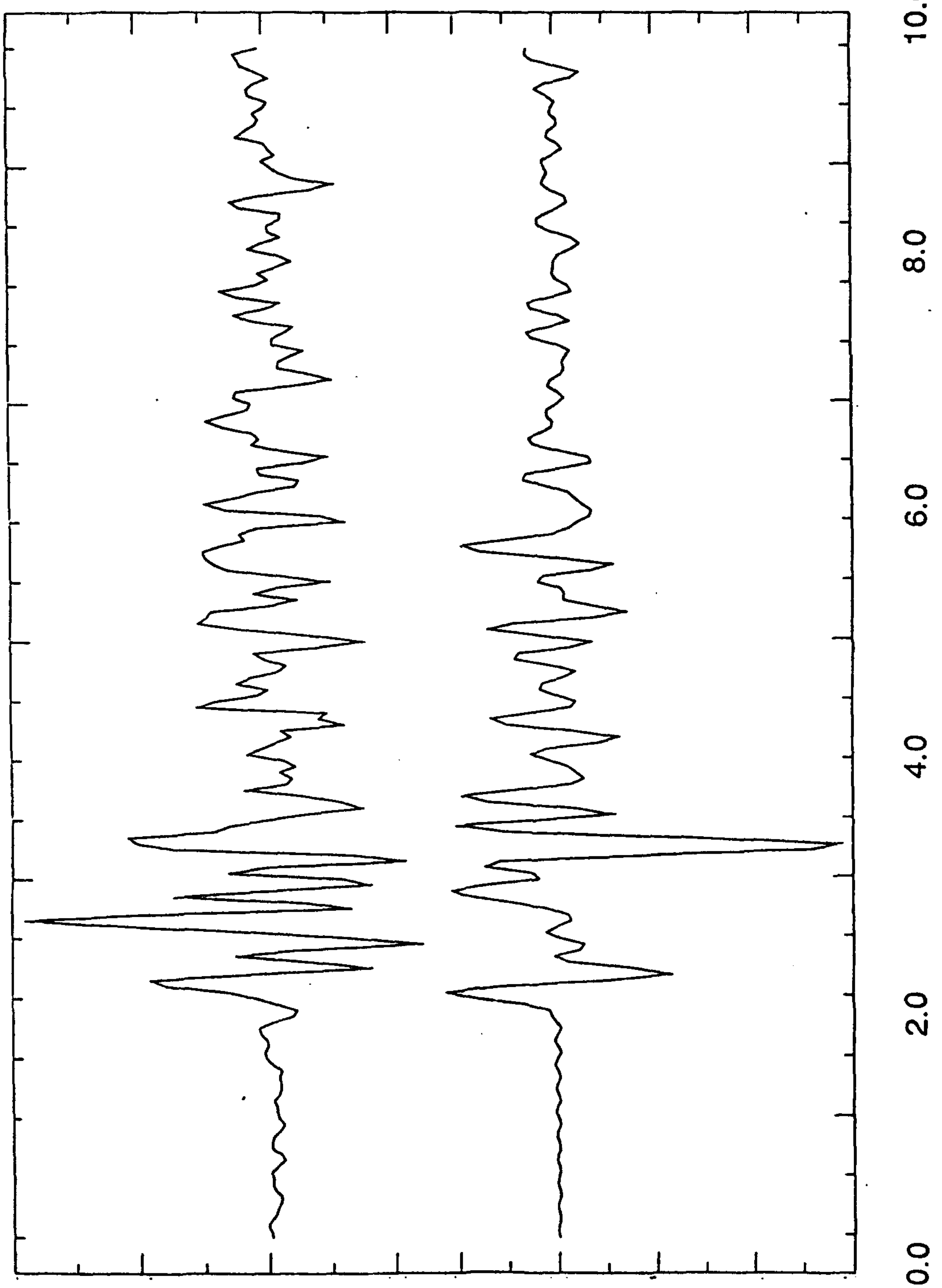


FIGURE 5 a



156 km

FIGURE 5 b



197 km

FIGURE 5 c

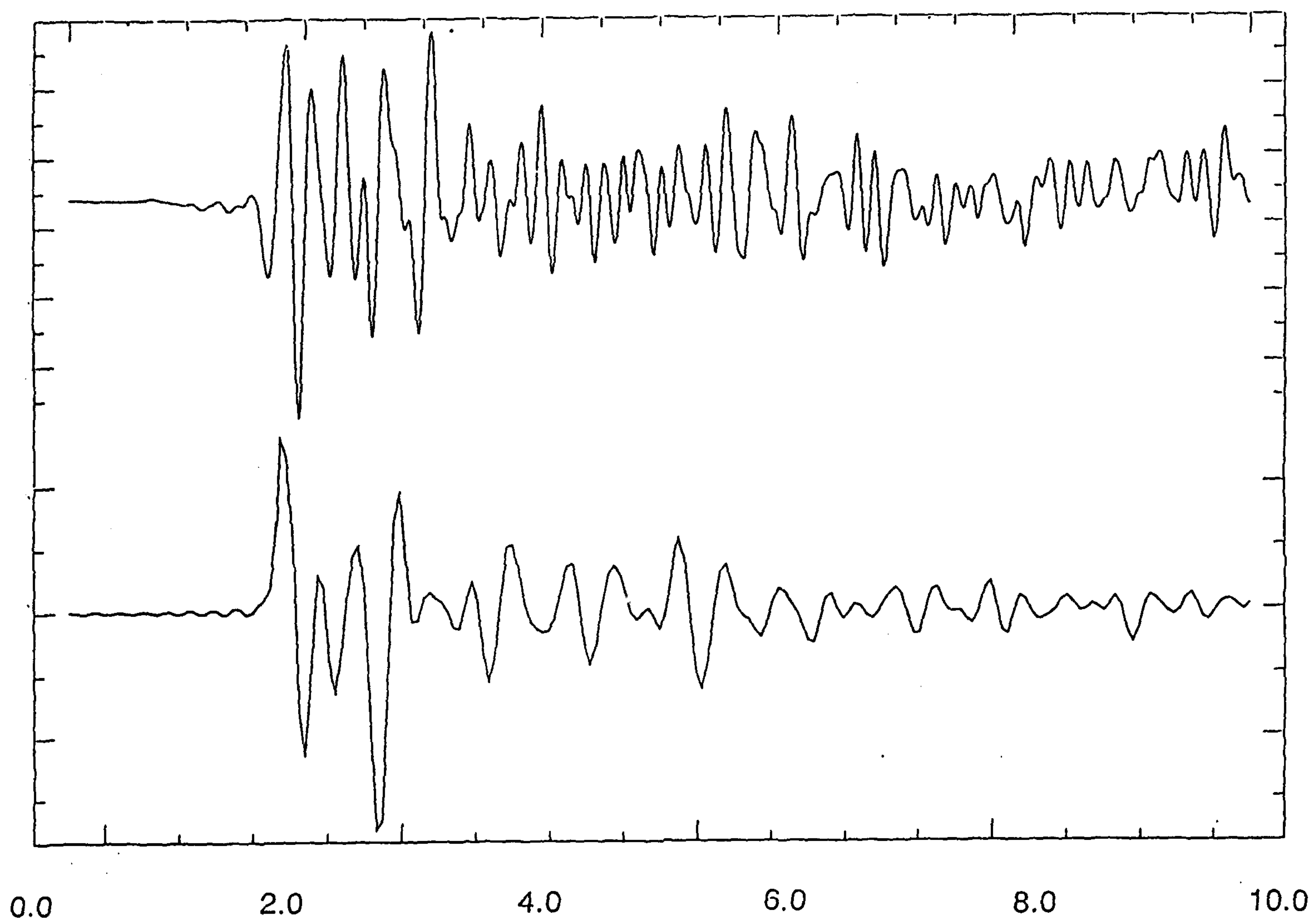
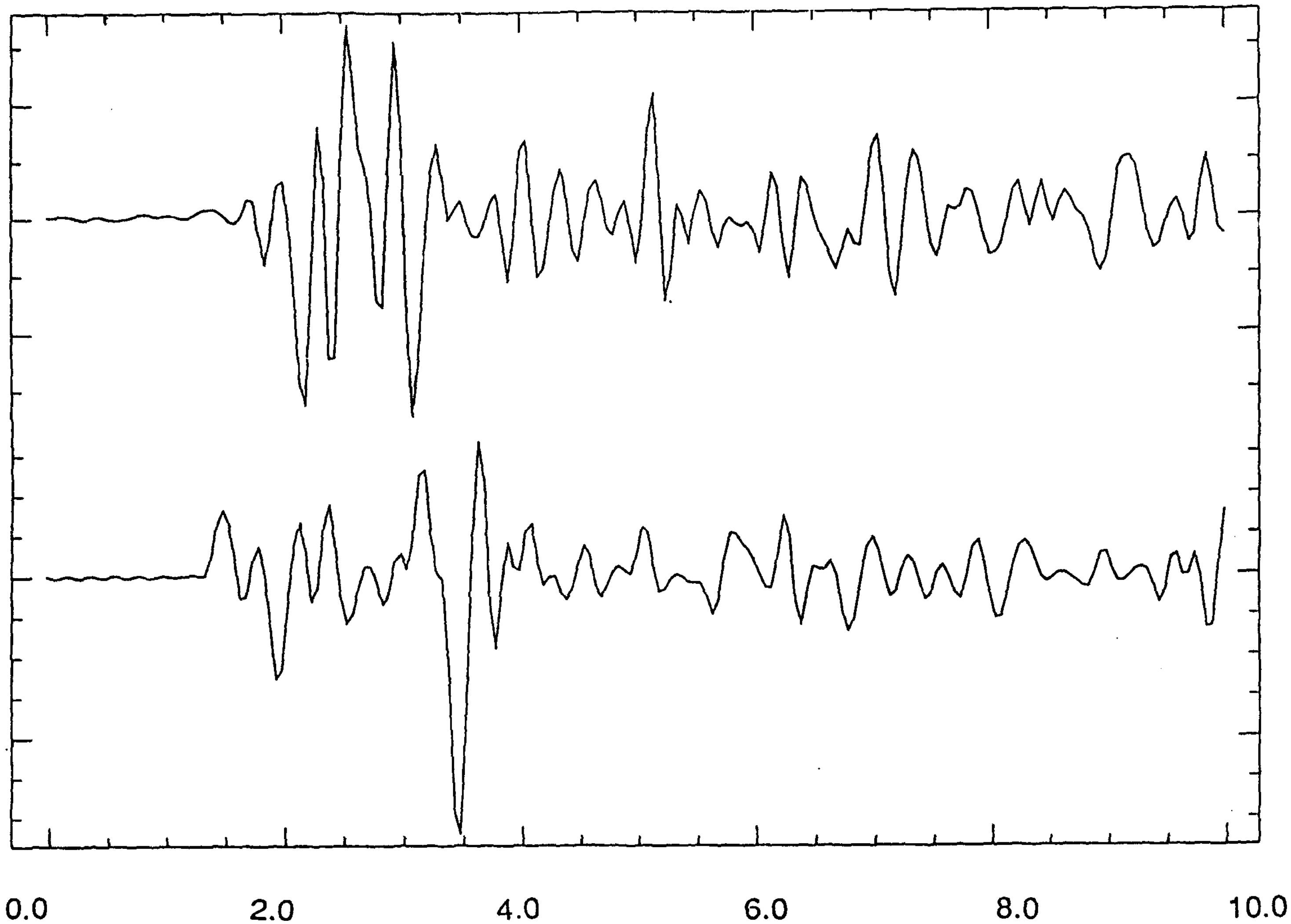


FIGURE 5 d



301 km

FIGURE 5 e

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